A precision TVG for echo ranging sonar

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Abstract

A sonar Time Varied Gain (TVG) circuit was designed in which the gain, as a function of time, is mathematically predetermined by theoretical equations that are programmed into the circuit by analog techniques. Essential to the design is a voltage controlled ac resistance device consisting of a transformer and two diodes. Use of this device as the output circuit of an amplifier results in a gain that, in decibels, is a linear function of the dc control voltage. This equivalence of decibels and dc voltages enables a simple analog computing circuit to satisfy the theoretical gain equations.

Introduction

A problem with echo-ranging sonars, remotely operated through a long or lossy cable, is the restricted dynamic range resulting from the cable transmission loss. Dynamic range requirements of the cable transmission system are greatly reduced by remote location of the sonar's Time Varied Gain (TVG) circuit. However, the additional problem of remotely controlling or adjusting the TVG can then only be avoided by anticipating the correct TVG circuit parameters and adjusting them before operation.

With the addition of a new side-scan sonar to the Naval Research Laboratory's Deep Ocean Search System, large cable loss in the side-scan signal channels made a remote TVG imperative. To alleviate the problems of preadjustment and avoid those of remote control, a new sonar TVG circuit was designed.

Objectives

A primary objective in this design was ease of preadjustment of the circuit parameters. The TVG need compensate only for the time variable factors and these are entirely included in the sound transmission losses. Thus, with the exception of fixed gain, the desired TVG curve is theoretically predetermined by the transmission loss equations. Ideally, in a circuit which closely approximates the theoretical curve, fixed gain is the only adjustable parameter. This adjustment includes source level, sensitivity, and target strength (or roughness in the case of a bottom scanning sonar) as well as the desired output level.

Since, in a practical circuit, the time varied gain correction covers at least several orders of magnitude, achievement of the above objective requires a simple mathematical relationship between gain and the controlling electrical quantity over an equivalent range of magnitudes. Such a relationship allows the control function to be derived through analog techniques to produce the desired time varied gain curve.

Voltage Controlled Resistance

In any gain control circuit there must be an electrically controlled circuit parameter and in this design its variation as a function of the control input must be mathematically described. The variable parameter used in this design is an ac resistance and it is controlled by a dc voltage. Figure 1 is a circuit diagram of the ac resistance device.

![Fig. 1 — A voltage controlled ac resistance circuit.](image)

The behavior of this circuit is based on the well known logarithmic relationship exhibited by junction diodes between the diode voltage and the forward conduction current. This may be described by the empirical equation:

\[
\frac{V}{V_0} = \log \frac{I}{b}
\]

where \( V \) = forward diode voltage

\( I \) = forward conduction current

and, \( V_0 \) and \( b \) are constants of the particular diode type. \( V_0 \) is the incremental voltage required to produce a ten-fold increase of current. Although the significance of \( b \) is theoretically unacceptable, since Eq. (1) defines it as the current which flows when the voltage, \( V \), is zero; the empirical equation is accurate over many orders of magnitude of current and may be regarded as valid over the range of practical applicability. For the diodes used in this application (1N4153, see Fig. 2) this range extends from currents of less than a micro-amp to a few milli-amps where heating effects take place.

Analysis

This analysis will assume that, in the frequency band used, the transformer approximates an "ideal" transformer. The center tapped secondary is balanced and although any primary to secondary turns ratio may be used, for the purpose of analysis, it will be assumed to be unity. The use of a control voltage, \( V_c \), here implies...
and the resistance reflected to the primary is:

$$R_L = \frac{2V_0 \log e}{b}$$

(3)

In terms of the control voltage, this is expressed:

$$R_L = \frac{2V_0 \log e}{b \times 10^{-\xi/V_0}}$$

(4)

This result was to be expected since, from Eq. (1), the small-signal resistance of each diode would be defined:

$$\lim_{\Delta I \to 0} \frac{\Delta V}{\Delta I} = \frac{dV}{dl} = \frac{V_0 \log e}{l}$$

and the resistance reflected to the primary is 4 times the parallel resistance of the two diodes. Equation (2), however, establishes the magnitude of signal voltage, $\xi$, which may be considered "small" and the linearity of the Voltage Controlled Resistance (VCR) circuit for finite signal levels. Re-writing Eq. (2) to include the small signal resistance, $R_L$, of the VCR we have:

$$R_L \Delta I = 2V_0 \log e \sinh \left( \frac{\xi}{2V_0 \log e} \right)$$

(5)

The term, $R_L \Delta I$, is the signal voltage which would be developed by the current $\Delta I$ in a perfectly linear resistance having the small-signal value, $R_L$.

In the linearity curve of Fig. 3, the voltage, $\xi$, is plotted against $R_L \Delta I$ as derived from Eq. (5), using the values, $V_0 = 0.11$, measured for 1N4153 diodes. Since $R_L$ may have any value as determined by $V_c$, the linear region is limited by the developed signal voltage, $\xi$, rather than the signal current, $\Delta I$.

**Gain Control**

Application of the VCR circuit for gain control involves using the controlled resistance as the load for a high impedance source, or "current pump", and allowing the ac voltage developed to be determined by VCR. A good example of such a source is a common base amplifier. It is an inherent characteristic of the common base configuration that, for high gain transistors, the output current is approximately equal to the input current. Thus the voltage gain is the ratio of the ac load resistance, $R_L$, to the emitter input resistance, $R_e$. 

**Fig. 2** — Measured forward conduction current vs. voltage for a 1N4153 diode.

**Fig. 3** — Linearity of the Voltage Controlled Resistance circuit.
Voltage gain – Power gain = $R_L/R_i$. (6)

Using the resistance of the VCR given by Eq. (4) as the load, the gain is:

$$Gain = \frac{2V_o \log e}{bR_i} \times 10^{V_o/V_0}$$

and expressed in decibels it is:

$$A (dB) = \frac{20}{V_0} (V_{co} - V_c)$$ (7)

where the voltage, $V_{co}$, has the value:

$$V_{co} = V_0 \log \left( \frac{2V_o \log e}{bR_i} \right).$$ (8)

With this circuit, decibels are equated with volts and the multiplication of gain factors is now reduced to the simple addition of dc voltages.

**VARIABLE GAIN AMPLIFIER**

An amplifier, constructed for the sonar TVG application, is shown in Fig. 4. The input resistance is approximately 50 $\Omega$. Substituting this value and the constants, $V_0$ and $b$, for the 1N4153 diodes into Eqs. (7) and (8), the gain in decibels is:

$$A (dB) = 178 (0.650 - V_c)$$ (9)

Unity gain (0 dB) occurs when $V_c = 0.650$ volts. Obviously (Eq. 6), this is the control voltage for which the resistance, $R_c$, is equal to the input resistance, $R_i = 50 \Omega$. The zero signal diode currents for this resistance are approximately 2 mA. As the voltage, $V_c$, is decreased, the gain increases at the rate of 178 dB/volt. At a control voltage of 0.3125, the diode currents are 2 $\mu$A, the small-signal resistance is 50 $\Omega$ and the gain is 60 dB. From Fig. 3 it can be seen that at an output of 0.1 volts, the gain is reduced 1 1/2 dB. Gain and voltage measurements confirm the theoretically derived equations above.

A characteristic resulting from the use of a tuned output transformer (Fig. 4) is that the bandwidth is inversely proportional to the gain. This is so because the $Q$ of the output circuit is proportional to the parallel load resistance. This feature restricts the noise bandwidth at high gain and simplifies the transformer design. The $L$ to $C$ ratio of the tuned circuit is chosen to assure adequate bandwidth for the signal at maximum gain. Care must be taken in coupling to a following stage that the VCR is not loaded as this would invalidate the gain equation.

Another characteristic is the result of the total absence of coupling or by-pass capacitors. The circuit recovers almost instantly from severe signal overload.

A common emitter amplifier can also be used effectively or the VCR can be used in the feedback loop of an operational amplifier. For a sonar preamplifier, however, the low noise amplifier illustrated appears suitable because it can easily be matched to a tuned transducer for high transducer gain.

**TRANSMISSION LOSSES**

Having established a mathematically predictable means of controlling the gain, it is now well to review the sonar transmission loss equations. The two principal losses which will be compensated in this system are spreading loss and absorption loss. There are other losses, such as that caused in a bottom scanning system by the time variation of angular displacement in the sonar beam. The dynamic range of these other losses, however, was considered acceptable in the NRL system, and their exclusion here in no way precludes refinements to the technique presented.

**Spreading Loss**

In this presentation, spherical spreading to and from the target will be assumed. This choice, however, is not essential to the design and, as will be seen, other spreading laws may be used by modification of a resistance ratio in the control circuit.

According to the spreading law assumed, the decibel loss in signal strength of the echo from a target at range $r$ is given by:

$$A (dB) = 40 \log r/r_o$$ (10)

The zero dB reference is the signal level which would be received from a target of equal strength at range $r_o$. Since the units of distance are arbitrary, the time units in a time varied gain correction for this loss are also arbitrary. The speed with which the correction curve is swept determines the units of distance and the fixed gain needed.

**Absorption Loss**

Unlike the spreading loss, which is independent of the units of distance, the absorption loss is taken to be an exponential time decay of the radiated sonic energy. As a function of the total distance, $x$, traveled by a sound pulse, the loss in decibels is $\alpha x$; and for a target distance, $r$, the two way loss in echo ranging is $2 \alpha r$. This loss increases at the constant rate of $2 \alpha r$ dB per second, where $c$ is the sound speed.

The total spreading and absorption loss that will be compensated in this system is given by:

$$A (dB) = 40 \log r - 40 \log r_o + 2 \alpha r.$$ (11)

It is convenient to retain the constant term, $40 \log r_o$, for clarity of explanation.

**CONTROL CIRCUIT**

To compensate the transmission losses by time varied gain control, the control voltage, $V_c$, must be varied as a function of
time such that the resulting gain matches the attenuation at any given time, \( t \), or target range, \( r = \frac{t}{c} \). The proper time function for \( V_v \) is found by equating the attenuation, Eq. (11), and the gain, Eq. (7), to obtain:

\[
V_v = E - 2V_0 \log r - V_0 \frac{2tr}{10}\]  
(12)

where \( E = V_0 + 2V_0 \log r \).

Figure 5 shows a circuit which generates the log function and sums the voltage terms of Eq. (12) using operational amplifiers. It requires a negative input voltage, \( V_1 \), that is directly proportional to range or time and a separate fixed input voltage, \( V_3 \).

\[3V_1 = V_c + 2V_0 \log \frac{2\beta r_0}{R_3bc}.\]  
(14)

Now, the quantity, \( \frac{2\beta r_0}{R_3bc} \), is the current, \( I_0 \), which flows in the feedback diode of Fig. 5 when the range is \( r_0 \). And from (7) and (1),

\[V_v = V_0 \log \frac{I_o}{b}\]

where \( I_o \) is the current in each of the VCR diodes when the amplifier gain is 0 dB. Thus,

\[V_3 = V_0 \log \left(\frac{I_o - I_3^2}{b}\right)^{1/3} \]

This is the voltage that would exist across a diode in which the current flow is:

\[I_3 = (I_o - I_3^2)^{1/3}.\]

In the NRL system a 1N4153 diode with a series resistor is used to generate the voltage, \( V_1 \), from a supply voltage. Since the current, \( I_o \), is already determined by the variable gain amplifier circuit, the diode current, \( I_3 \), is used to adjust the amount of input current, \( I_o \), and hence the range, \( r_o = \frac{I_o R_3bc}{2P} \)

at which the spreading loss is referenced to 0 dB. At this range, the amplifier gain is \( 2\alpha r_o \) (dB).

In the NRL system, a 60 dB TVG range provided by a single controlled amplifier was considered inadequate for the sonar range coverage desired. Therefore two controlled amplifiers were cascaded with suitable isolation to provide a greater, and more easily attainable, total TVG range of 80 dB.

For two amplifiers in cascade, the gain, \( A \) (dB), in Eq. (7) is doubled. Recalculation of the control circuit constants gives:

\[\frac{R_0}{R_2} = 1, \quad \frac{R_0}{R_1} = \frac{V_0 R_3bc}{40\beta}, \quad I_3 = \sqrt{I_o - I_3^2}.\]

Considering its effect, it is advisable to keep a close tolerance on the resistance ratio, \( R_d/R_2 \). This ratio is determined not only by the number of gain controlled amplifiers, but also by the exponent in the spreading law used.

It is important that the voltage ramp generator which generates the voltage, \(-\beta t\), have an intercept of zero. Zero time, of course, is the moment the transmitter is pulsed. A voltage error here is equivalent to a constant range error in the TVG correction curve. At long ranges a small error has negligible effect, but at short ranges it can be significant. Although a negative slope was used to describe the circuit operation, a positive slope is also practical by simply reversing all of the diodes in the VCR and control circuits.

RESULTS

It is convenient that, because the required input voltage, \( V_1 \), to the control circuit is proportional to time, leisurely measurements can be made of the gain corresponding to any instant of time, \( V_1/\beta \). Such measurements indicate that the circuit conforms to the theoretical equations for which it was designed. The TVG still awaits trial in an echo-ranging system.